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GERMANIUM REQUIREMENTS FOR NATIONAL DEFENSE

Donald A. Fink
Julia Culver-Hopper

July 1991

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Office of the Assistant Secretary of Defense
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13. ABSTRACT ***(Maximum 200 words)***

Germanium, one of the most important of the advanced electronic materials, is used in semiconductor devices, fiber optic systems, and infrared sensors for ships, aircraft, missiles, tanks and anti-tank units. Because of its importance in these applications, germanium was added to the National Defense Stockpile in the early 1980s. This study estimates the appropriate amount of germanium to be held in the stockpile, given DoD's current assumptions for stockpile planning. Because of the dearth of publicly available data on germanium supplies and demands, the analysts based these estimates on data gathered from Service Program Offices and industry and company officials throughout North America. The study was conducted in support of DoD's ongoing effort to review and update the requirements for strategic and critical materials.

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GERMANIUM REQUIREMENTS FOR NATIONAL DEFENSE

A-1

Donald A. Fink
Julia Culver-Hopper

July 1991

INSTITUTE FOR DEFENSE ANALYSES

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PREFACE

At the special request of the Department of Defense, the Institute for Defense Analyses (IDA) conducted an assessment of the merit of stockpiling germanium in the National Defense Stockpile. Formal IDA review of this paper has been completed. Thanks are expressed to the reviewers -- Dr. William Hong, Dr. Robert Oliver and Dr. Richard Van Atta (all of IDA) as well as to Mr. Thomas Llewellyn, Germanium specialist at the U.S. Bureau of Mines, Department of Interior. The reviewers all concurred in the principal findings of the study. The outstanding and timely assistance of Dr. David R. Graham and Ms. Shelley Smith, as well as that of Ms. Barbara Fealy, Ms. Teresa Dillard, Ms. Angela Toney, Mrs. Donna Banks and Mrs. Marie Olsson, also all of IDA, is gratefully acknowledged.

The support of scores of private corporations and their executives in providing crucial data for this study is gratefully acknowledged. The help of numerous military agencies is also recognized, in particular the Army Night Vision Center and the Naval Research Laboratory.

A Special Note: The senior author of this paper, Captain Don Fink, USN (Ret.), passed away early on the morning of May 15, 1991. He is sorely missed, not just for his expertise in this area, which was extraordinary, but also for his comradery, intellectual excitement, and his terrific sense of humor.

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EXECUTIVE SUMMARY

Germanium, one of the most important of the advanced electronic materials, is used in semiconductor devices, fiber optic systems, and infrared sensors for ships, aircraft, missiles, tanks and anti-tank units. Because of its importance in these applications, germanium was added to the National Defense Stockpile in the early 1980s. This study estimates the appropriate amount of germanium to be held in the stockpile, given DoD's current assumptions for stockpile planning. The study was conducted by the Institute for Defense Analyses at the request of the Department of Defense (DoD) as part of DoD's ongoing effort to review and update the requirements for strategic and critical materials.

A. METHODOLOGY

There is a large technical literature on germanium which reflects the fact that a germanium transistor, developed in 1948, triggered the post-World War II surge of modern electronics. The chemistry of this element has probably been explored as intensively as that of any other element. The economics of the industry producing germanium have not been as systematically studied, however, and the industry's activities have not been well documented. Furthermore, the military applications of germanium have not previously been estimated in the context of the current stockpile planning scenario.[1]

The methodology employed in this study is dictated by the limitations of the publicly available data on germanium supplies and demands. To estimate supplies, and supply expansion capabilities, the researchers interviewed industry and company officials throughout North America. To estimate demands, the researchers contacted program offices in the Army, Air Force, and Navy to identify weapons systems that contain germanium. These discussions revealed that the significant demands for germanium in the planning scenario would be confined to infrared systems. The program offices identified the contractors supplying such systems, who were then consulted for estimates of the amount of germanium contained in each component or sub-system.

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1 Dr. Marta Kowalczyk's 1984 assessment, *Supply of Germanium for DoD Needs*, IDA Paper P-1752, has provided very useful background for this project, however.

Total military requirements were estimated by multiplying these estimates for individual infrared devices by estimates of weapon production requirements for the stockpile planning scenario. This scenario assumes a 1-year warning period, an intense global conflict lasting a few months, followed by a mobilization to rebuild forces to levels that equal or exceed pre-conflict levels, and a second conflict period. During the warning year, supplies are assumed to be available from normal peacetime sources. Only North American sources of supply are assumed available to meet military and essential civilian demands once the conflict begins.

Weapon production requirements for this scenario were estimated using the Joint Industrial Mobilization Planning Process (JIMPP) Model.[2] Essential civilian requirements were estimated by examining recent consumption and substitution trends.

B. FINDINGS AND CONCLUSIONS

Germanium consumption would increase from the current rate of 36 MT per year to an estimated 48 MT per year in the war years (Table ES-1). Military consumption nearly doubles, from 23 MT per year to 42.7 MT per year. Civilian use drops sharply, however, because most civilian use is not considered "essential" for the purpose of calculating stockpile goals.

Ample supplies to meet these germanium demands are available in Canada and the United States, provided that zinc mining continues and that steps are taken during the warning year to augment some phases of domestic germanium processing capacity. The supply process for germanium entails three main phases: 1) zinc mining and smelting, which yields germanium in trace amounts of less than 1 percent in the smelter residues; 2) extraction, which concentrates the germanium in these residues to levels of 20 percent or more; and 3) refining, which creates high-purity germanium through a series of chemical and heat-treating process. The main bottleneck in expanding production to meet the scenario requirements lies in the limited capacity for extraction, because little extraction is done within North America today. If domestic extraction capacity is increased during the warning year to match current zinc smelting output--a readily feasible option--domestic supplies will exceed demand in each of the three war years.

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2 The *Report of the Secretary of Defense to the Congress on National Defense Stockpile Requirements*, 1989, describes the JIMPP process and scenario.

Table ES-1. Germanium Supply and Demand for NDS Planning

(Metric Tons)

	Current	Scenario War Years 1	2	3
Demand				
Civilian [a]	13	5.4	5.4	5.4
Military	23	42.7	42.7	42.7
Total	36	48.1	48.1	48.1
North American Supply				
Mining [b]	30	70+	70+	70+
Extraction [c]	6	70+	70+	70+
Refining	36	100+	100+	100+
Total (Limited by Extraction Bottleneck)	-	70	70	70
Net Supply	-	21.9	21.9	21.9

a Essential civilian uses included in war years.

b Feedstock of low-concentrate germanium is more than ample from zinc mining and from existing mine residue piles.

c Assumes restart of Hecla extraction facility and construction of a 30 MT per year extraction facility during the warning year.

There are three possible future developments to monitor, as they may alter the supply and demand estimates presented here: First, germanium processing capacity is highly concentrated in a handful of firms, so North American capacity could change quickly if firms enter or exit the industry. Second, technological change may reduce the military's reliance on germanium for infrared devices. Third, more systematic recycling of the germanium contained in surplus or damaged infrared devices could provide a cost-effective substitute for stockpiling virgin germanium.

The National Defense Stockpile has a germanium inventory of about 68 MT--more than one-year's wartime consumption for the stockpile planning scenario. Thus, the inventory should be ample to meet any shortage that may develop while domestic processing capability is being expanded, and to hedge against uncertainty. This study concludes, therefore, that there is no need to buy additional germanium for the National Defense Stockpile.

C. ORGANIZATION OF THE PAPER

Part I of this paper characterizes germanium and presents general supply and demand information. Part II examines defense germanium requirements and presents the database developed for this study. Part III estimates essential civilian germanium requirements. Part IV compares requirements and supplies and summarizes the principal findings of the study.

I. AN OVERVIEW OF GERMANIUM SUPPLY AND DEMAND

A. TECHNICAL CHARACTERIZATION OF GERMANIUM

Germanium (Ge) is a silvery-white semiconductor[1] that is opaque to ultraviolet and visible light but transparent in the infrared (IR) frequencies. Its chemical properties reflect its location in the periodic system below carbon and silicon but above tin and lead: its properties lie between those of metals and insulators.

Ge is a strategic material because of its superior opto-electronic properties in the IR radiation spectrum (8 to 12 micron range of the light spectrum). There is no competing material with an index of refraction as high as that of Ge (4.0) that also has Ge's excellent transmission characteristics.[2] Ge also has very low signal dispersion in the 8 to 12 micron range, which means that a Ge lens will tend to bring all the wavelengths in the range very close to the same image plane. This facilitates good imaging performance in IR optical systems.

There are problems associated with Ge use in IR systems. One is that its index of refraction deteriorates rapidly at temperatures in excess of 100 degrees centigrade with the result that the IR image goes out of focus.[3] This means that IR systems frequently have to be refrigerated internally to protect them from image degradation at high temperatures. Unavoidably, this increases the bulk, complexity, and cost of IR systems. Ge is also subject to surface erosion, pitting, chipping, and cracking from various causes. Finally, it is expensive and difficult to work with in manufacturing.

Although most forms of Ge are nontoxic, the tetrachloride, which is used in optical fiber manufacturing, undergoes hydrolysis in the lungs, yielding hydrochloric acid, a toxic substance. Exposure to the tetrachloride, therefore, can lead to internal bleeding. This is

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1 A semiconductor is a material in which electric current is carried by electrons or holes and whose electrical conductivity when extremely pure rises exponentially with temperature and may be increased by many orders of magnitude by "doping" with certain materials.

2 Transmission is defined as the ratio of the intensity of light emerging from a device to the intensity incident on the device.

one of the reasons why the tetrachloride was rejected as a form of GE suitable for the National Defense Stockpile (NDS) by the ASM International advisory pancl on Ge in 1987.[4]

B. GERMANIUM SOURCE MATERIALS

Most primary Ge is recovered as a byproduct from residues generated by the smelting and refining of zinc. While the Ge content of zinc ores various widely, all zinc ores contain at least some Ge. There are some zinc ores that are relatively rich in Ge, containing 150 to 250 parts per million (PPM) or more. There is no zinc deposit, however, containing sufficient Ge to make Ge recovery a significant consideration in decision-making about whether to mine the deposit. Ge is also found in some coals, especially those in the United States. Given the magnitude of known coal deposits, the ultimate potential availability of Ge is enormous relative to foreseeable demand. At the present time, however, Ge is recovered commercially from coal ash only in the Soviet Union, where coal ash processing accounts for approximately 90 percent of primary Ge production.[5]

Although both the United States and Canada possess large reserves of Ge-bearing zinc ores and coals, Cominco Ltd in Canada and Jersey Miniere Zinc in the United States are the only North American firms currently producing primary Ge source materials.[6] Jersey Miniere is a subsidiary of Asec-Union Miniere, a Belgian company. There is a third company, Hecla Mining Corp., also of Canada, which owns a Utah mine and refinery yielding gallium (Ga) and Ge as well as low concentrations of copper, zinc, lead, and silver. (This is the only mine in the world developed ir. arge part because of its Ge resources.) However, commercial production at this facility was suspended in 1990

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3 R.E. Fischer, "IR System Design: The Basics" *The Photonics Design & Applications Hardbook*, (Pittsfield, MA: Laurin Publishing Co., 1990).

4 *Assessment of Quality and Material Form of Germanium for the National Defense Stockpile*, Final Report of ASM International Panel. ASM International, Metals Park, Ohio, 1987.

5 The chemistry of Ge recovery from coal ash is well understood and facilities for recovering the metal from this source could be installed in the United States and brought into production in less than 2 years in an emergency. The potential volume of Ge recovery from the coal ashes currently produced in American coal-fired power plants is far beyond total U.S. demand.

6 Although Johnson Matthey Ltd terminated its refining activities at Cominco's Trial, British Columbia, smelter in October 1990, Cominco will continue to recover Ge from the concentrates processed at the smelter. The reason is that Ge must be removed from the processing circuit before recovery of indium can be carried out. Since the market for Indium is growing and profitable, Cominco's capacity for Ge will be maintained. Telephone interview with Mr. K. Ritala, Johnson Matthey Sales Department, 30 October 1990.

because of adverse market conditions and difficulties in the processing plant. Hecla could resume production quickly when market conditions warrant.

Several other companies, including Houston Mining, have explored ore bodies containing Ge either in Canada or in the vicinity of the Hecla mine in Utah. While several of these deposits have been favorably evaluated, the world Ge market is currently awash with material from the Soviet Union and the Peoples Republic of China. It is unlikely that new mines will be developed until market conditions improve significantly.

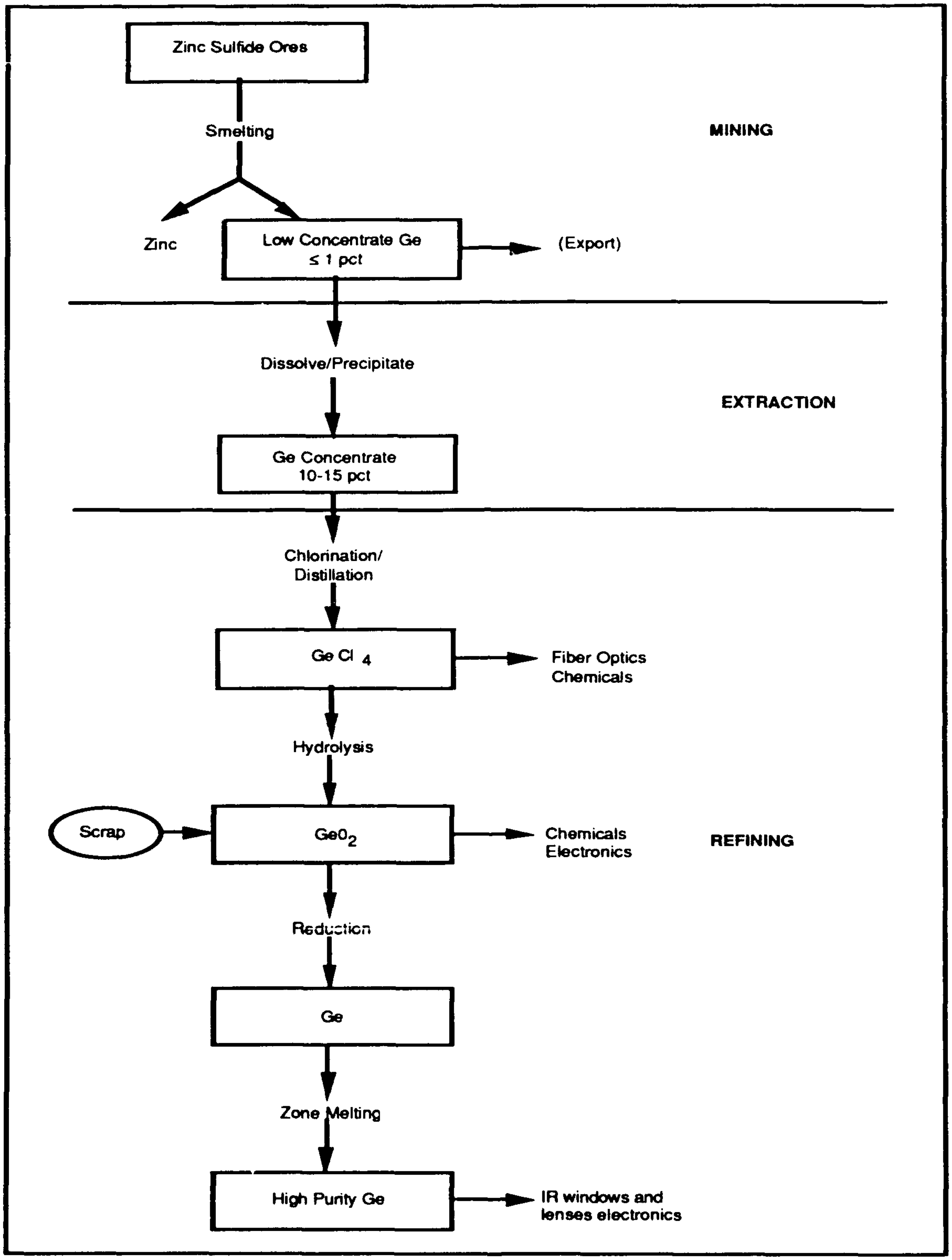
C. STRUCTURE OF PRODUCTION IN THE GERMANIUM INDUSTRY

Figure I-1, below, presents a graphical view of the flow of production in the Ge industry. Three main phases of processing are identified: mining, extraction, and refining. As the figure indicates, source materials from the zinc smelters include trace amounts of Ge ($\leq$ 1 pct) in the smelter residues. Ge is concentrated in an extraction process involving dissolution and precipitation to achieve a Ge composition of 10 percent or more. In the refining process, this zinc is converted to germanium tetrachloride and then to pure germanium dioxide. The dioxide is then reduced to metal, although some is also marketed directly to the chemicals and electronics industries. The dioxide, moreover, is also the principal form in which primary Ge materials travel internationally. Reduction metal produced from the dioxide is not pure enough for most electronics applications and is therefore subjected to zone refining for further purification. Zone melting yields a very pure polycrystalline metal suitable for almost all electronic and optical applications.

Refiners making zone refined Ge may sell it in bars or ingots or further process it themselves. Eagle-Picher, for example, sells bars but also fabricates a percentage of its Ge output into blanks, which are used by optical firms to make Ge lenses and windows. Eagle-Picher also manufactures small quantities of Ge wafers used as substrates for GaAs-on-Ge solar cells destined for space applications, in particular the NASA space station.

On average, about 50 percent of the refined Ge produced in the United States is converted to end-use products, while the remainder becomes "new" scrap available for recycling.[7] Since new scrap is pure metal, almost all of it can be recycled by remelting it and repeating the stages of intermediate processing.

[7] Telephone interview with Mr. Richard Sharman, President, Exotic Materials, 27 July 1990.



Adapted From: U.S. Department of Interior, "The Economics of By Product Metals," Bureau of Mines Information Circular, 8570, 1973.

Figure I-1. The Structure of Germanium Processing

End-use systems incorporating Ge sometimes break down, wear out, or suffer damage, generating "old" scrap in the process. This material may or may not be recovered and recycled, depending on the nature of the end-use application. Ge used in most non-optical electronic applications is not generally recovered and recycled. Ge windows and lenses in opto-electronic systems, on the other hand, can be recycled; considerable amounts of it are recycled each year. Recycling of Ge from military IR devices is discussed separately in Chapter II, Section C.

There are thus four stages of production at which capacity bottlenecks could develop in the Ge industry:

1. Mining
2. Extraction
3. Refining
4. End-use fabrication and scrap remelting

The fourth stage, end-use element fabrication, is difficult to summarize because it consists of many firms, some very large and others very small, engaged in converting primary Ge into optical elements for incorporation into end-use devices. Entry into this stage of Ge processing is relatively easy, and there is said to be ample domestic capacity, especially in the IR systems field where the United States is the world leader in technology.[8] The authors discussed scrap recycling with representatives of Exotic Materials, Inc. (EMI), the largest processor of new scrap in North America.[9] According to EMI executives, the company currently has a melting capacity of 22 MT per year expandable to 35 MT per year in 6 months. Melting is a simple process, and most companies make their own equipment for it. Many of the optical element producers, on the other hand, maintain capacity for remelting the Ge scrap they generate. According to industry experts, fabrication and melting present no bottleneck potential at the present time. Consequently, no effort was made in this study to define and measure capacity at this stage of production.

The North American supply situation with respect to mining, extraction and refining is discussed below.

---

8 Final Report of the Joint Precision Optics Technical Group (JPOG), Joint Group on the Industrial Base, Joint Logistics Commanders, Wright-Patterson AFB, June 1987.

9 Telephone interviews with Mr. Richard Sharman and Mr. Rod Randolph, EMI, 9-12 October 1990.

D. NORTH AMERICAN MINING AND EXTRACTION

Jersey Miniere derives its Ge source materials from Tennessee zinc ores smelted at Clarksville, Tennessee. According to Roskill Information Services,[10] this smelter has an annual capacity to generate at least 30 metric tons (MT). A Ge market report published recently by Meldform Metals Ltd in England indicates that ' ion Miniere in Belgium is currently receiving about 24 MT/yr of Ge from this smelter.[11] Since the zinc smelter is not operating at capacity, it is clear that it could produce 30 MT/yr of Ge in source materials during an emergency. During an emergency, it is reasonable to assume that the U.S. government would divert this material from export to domestic refiners for processing if need be. To do this, however, would require establishing additional on-shore extraction capabilities. Industry executives indicate this capability could be established within the 1-year warning period, provided adequate solvent and other supplies were available.[12]

The Cominco smelter at Trail, British Columbia, receives zinc concentrates from several Canadian mines but increasingly depends on its massive ore deposit in Alaska (Red Dog mine) for feedstock. Cominco constructed a Ge refinery some years ago but sold it recently to Johnson Matthey Ltd, a British firm, along with the rest of its Electronic Materials Division.[13]

Johnson Matthey executives indicate that the Cominco facilities at Trail currently have a Ge recovery capacity of 6 MT per year, expandable in 6 months to 15 MT and in a year to 20 MT.[14] The solvent extraction process utilized by Cominco lends itself to rapid expansion if feedstock is not a constraint. Note in this context that Trail operated for many years without recovering Ge from its zinc concentrates. The Ge values, therefore, passed through to the tailings piles, and these piles constitute a potential emergency source of large additional quantities of primary Ge feedstock.

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10 *The Economics of Germanium 1990*, Sixth Edition. Roskill Information Services Ltd, London, England, pp. 72-73. Roskill is a metals information service operating on a worldwide basis.

11 Germanium, Report Number 8, Meldform Metals Ltd, London, England, August 1990.

12 Telephone interview with Mr. Jack Adams, Vice President, , Eagle-Picher, June 26, 1991.

13 Note, however, that Johnson Matthey has recently decided to leave the Ge market, at least for the time being, because of adverse market conditions.

14 Telephone interview with Mr. Douglas Neugold, Sales Director, Johnson Matthey Ltd, 2 July 1990. Because of the strong market for Indium, Trail is currently extracting about 7 MT of Ge per year of Ge.

The Hecla Mining Corp. facility in Utah has a current annual capacity of about 15 MT of Ge, expan..ble in 6 months to approximately 20 MT.[15] As noted above, the plant is currently shut down.

In summary, so long as zinc mining continues throughout the planning scenario, the supply of low-concentrate germanium in zinc mining residuals will be ample, particularly given the residuals in storage at zinc mines such as at Trail, B.C. Extraction capability is presently limited, as shown in Table I-1, but can be expanded sharply within the warning year.

Table I-1. Estimated North American Extraction Capacity (Metric Tons)

Producer	Current	6-Month Expansion	12-Month Expansion
Hecla Mining, UT	(15)*	20	20
Cominco, Trail, BC	6	15	20
Other (Jersey Miniere, Eagle-Picher)	0	30	30+
Total	6	65	70+

* Facility is not currently in production.

E. NORTH AMERICAN REFINERY CAPACITY

Ge refining capacity is maintained by four North American companies: Atomergic Chemetals Corp., Eagle-Picher Industries, Cabot Corp., and Johnson Matthey Ltd. A number of other firms maintain zone refining foundries, however, and process materials similar to Ge. These firms would probably be able to refine Ge scrap but would not be able to reduce primary source materials to intrinsic metal without substantial investment in new facilities.

Eagle-Picher (EP) has a current refining capacity of 24 MT per year expandable to 48 MT per year within 6 months.[16] According to EP executives, a further major expansion in capacity could be achieved in 6 additional months. Johnson Matthey (JM) has a current

[15] Roskill, p. 70.

[16] Telephone interview with Mr. Jack Adams, Vice President, Eagle-Picher, 12 September 1990. Mr. Adams indicated that his company already has most of the equipment it would need to double its current capacity. It should be noted that Ge refining is a chemical, not a pyrometallurgical technology, and does not require massive production facilities that take years to build.

refining capacity of 6 MT per year expandable to 12 MT per year in 6 months.[17] JM, however, reorganized in October 1990, closing its refining facilities at Trail. No decision has been made as yet concerning the disposition of the Ge refining capacity. Consequently, this capacity will not be involved in the calculations which follow. Cabot's current refining capacity is 10 MT per year expandable to 15 MT per year in 6 months.[18] Atomergic has 2 MT per year of Ge refining capacity, expandable to 3 MT per year in 6 months.[19] There is no Ge refining capacity in Canada at the present time.

Thus, total North American refining capacity is as shown in Table I-2, below. According to EP and JM executives, total North American capacity could be expanded to 100 MT per year during the 12-month warning period in the stockpile planning sceanario.

Table I-2. Estimated North American Ge Refining Capacity (Metric Tons)

Producer	Current	6-Month Expansion	12-Month Expansion
Eagle-Picher	24	48	60+
Cabot	10	15	15+
Atomergic	2	3	4
Johnson Matthey	(6)*	(12)*	20*
Total	36	66	100+

* Facility is not currently in production.

EMI indicates that in 12 months its melting capacity could be expanded to levels far beyond what would be usable in terms of scrap availabilities. Hence, melting was not judged to be a bottleneck in the produce process.

The capacity discussion presented here is summarized in Table I-3, below. None of the expansion estimates in this table represents the product of a "crash" effort.

17 Telephone interview with Mr. Hugh Kennedy of JM, 12 September 1990.

18 Telephone interview with Mr. Fred White, Cabot, 10 October 1990.

19 Telephone interview with Mr. Thomas Llewelyn, Ge specialist, U.S. Bureau of Mines, 25 October 1990.

Table I-3. Summary of North American Ge Capacities (Metric Tons)

Production Stage	Current	+ 6 Months	+ 12 Months
Mining (plus Ge content in Residue Piles)	~30	60(+ residues)	70(+residues)
Extraction	6	65	70+
Refining	36	66	100+
Fabrication & Scrap Melting	ample	ample	ample

F. STRUCTURE OF GE CONSUMPTION IN THE U.S.

Reliable Ge consumption data are scarce. Utilizing data developed by the U.S. Bureau of Mines (BoM), Roskill has estimated U.S. consumption by end-use sector since 1980 (Table I-4).

The overall trends in these data are seen more easily in Figure I-2, below, which plots total Ge consumption for all end uses and total consumption minus usage in IR systems. The latter is about 90 percent military in nature. Figure I-2 demonstrates that total U.S. Ge consumption has been relatively flat since 1984, while consumption other than in IR systems has declined steadily since 1982. Note in Table I-4 the sharp decline of Ge consumption in optical fibers and semiconductors.

Ge has lost markets in semiconductors to cheaper substitutes.[20] This is also true in the detector market. Optical fiber consumption, on the other hand, has declined for reasons noted in Chapter III, Section B, of this report. New applications for optical fibers had been made in the armed forces, but few of them require Ge doped fiber. The TOW missile, for example, uses considerable optical fiber that is not Ge doped. Optical fibers are also finding their way into military aircraft and Navy ships, but, again, these are all short-range applications not requiring Ge doped fiber.

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20 See Appendix A.

Table I-4. Estimated Ge Consumption by End-Use Sector (Metric Tons)

Year	IR Systems	Optical Fiber	Detectors	Semi Conductor	Others	Total
1980	12.8	6.4	3.2	8.0	1.6	32.0
1981	15.2	5.7	3.8	8.7	4.6	38.0
1982	18.1	6.7	5.0	7.6	4.6	42.0
1983	17.5	5.25	3.5	5.25	3.5	35.0
1984	21.0	5.25	3.5	1.75	3.5	35.0
1985	24.7	5.7	1.9	1.9	3.8	38.0
1986	24.7	4.6	1.9	1.9	4.9	38.0
1987	26.0	4.0	2.4	2.0	5.6	40.0
1988	26.8	3.2	2.8	2.4	4.8	40.0
1989	23.4	2.2	2.9	2.9	4.7	36.0

The Navy is considering a new undersea submarine detection system to replace the aging sound surveillance system. This system may require Ge doped optical fiber. No firm decision has been made on this project, however, and it may not be approved given the current budget situation and the reduced level of friction between the United States and the Soviet Union. If it is approved, it is likely to require somewhere between 2 MT and 3 MT of Ge.

The trend in optical fiber technology is towards smaller diameter fibers requiring less Ge dopant per line-mile of cable. This trend has played a role in reducing Ge consumption in optical fibers in recent years. There is also research underway on optical fiber systems that will require no Ge at all. All factors considered, the optical fiber market is not a growth area for Ge.[21]

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21 Optical fiber manufactures can use Ge in almost any form. Most, however, obtain Ge in the form of the tetrachloride, which is converted to the dioxide during the optical fiber production process.

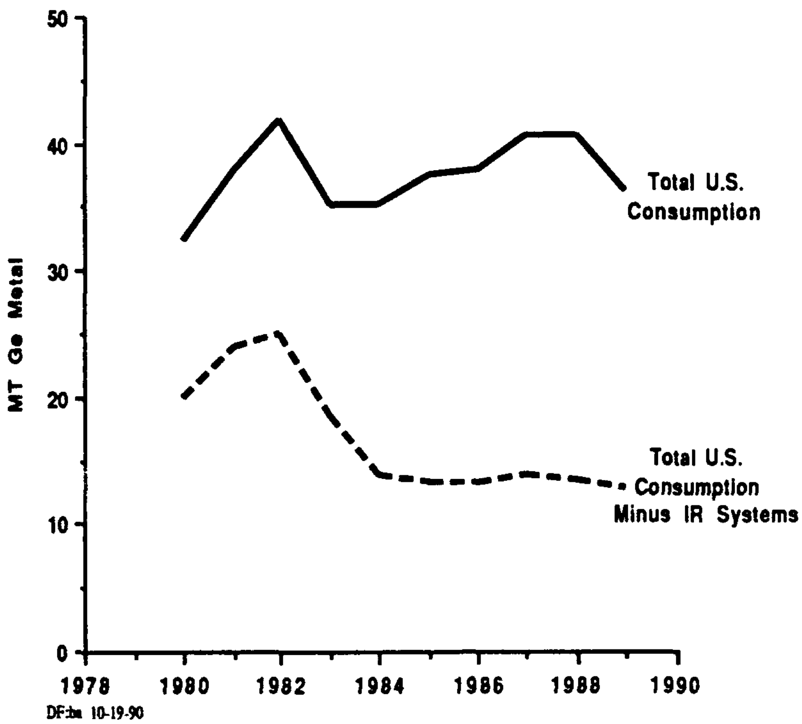

Figure I-2. U.S. Germanium Consumption 1980-89

The "other" category of Ge end-use includes catalysts. On a world-wide basis, the catalyst market for Ge is important because in Europe and Japan germanium dioxide is used as a catalyst in the reproduction of polyethylene terephthalate polymer. This material is used in making plastic food and drink containers. However, Ge is not used for this purpose in the United States. It is not in any case a military application for which there would be emergency requirements.

There are rumors that Engelhard and a Japanese company have jointly developed a germanium catalyst for use in automotive catalytic converters. The catalyst responds to air pollution standards in Western Europe and Japan, requiring removal of nickel from automobile emissions. EPA standards in the United States do not require nickel removal, so it is unlikely that American producers will adopt the material, except for exports, assuming it does appear on the market as a successful technology. This application, therefore, generates no emerging requirements.

Another new application for Ge is in solar cells for spacecraft. It has been found that a solar cell consisting of a thin layer of gallium arsenide on a Ge wafter is a more efficient producer of solar power than has previously been available.[22] Eagle-Picher is producing wafers for Applied Solar Energy, a California company that grows the cells and sells them to Lockheed. The latter is the prime contractor for the NASA space station project. The space station project may ultimately require considerable Ge for solar power generation. But again, this application has no relevance to national defense and is unlikely to continue during time of war. Ge solar cells are also used in military satellites, which do have national defense implications. However, it takes 3 to 6 years to build a space satellite. Not many are likely to be constructed from start to finish during a 3-year war scenario.

The bottom line of this analysis is that the only significant national defense requirement for Ge is in the manufacture of IR systems. At the present time, the military IR market is consuming about 21 MT of intrinsic grade Ge per year, according to BoM estimates. Meldform Metals puts IR consumption in the United States at approximately 17.5 MT per year. This represents a relatively high level of military demand because all of the armed forces are currently buying second- and third-generation IR devices for their night vision navigation systems and fire control systems, including those in missiles. Some of the third-generation systems use no Ge at all.

Note that current military consumption of Ge for IR systems (21 MT) represents less than half of the current North American primary Ge capacity shown in Table I-1, about 58 percent of the current North American Ge refining capacity shown in Table I-2, and about 28 percent of the total refining capacity that could be available 6 months into an emergency. This comparison neglects scrap recycling and thus heavily overstates the demand for refining capacity implied by the current level of IR consumption.

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22 Note, however, that the Solar Energy Research Institute has achieved a photovoltaic cell rating of 31.8 percent with a complex cell using indium phosphide. Photonics Spectra, November 1990, p.8.

II. DEFENSE SECTOR GERMANIUM REQUIREMENTS

A. THE STOCKPILE PLANNING SCENARIO

The current scenario for stockpile planning scenario developed by the Office of the Secretary of Defense and the Joint Staff is commensurate with Cong essional guidance for stockpile planning. The scenario entails a 1-year warning period, intense warfare for a few months months, followed by over two years of force rebuilding. Estimated stockpile requirements are based on a year-by-year comparison of military and essential civilian demands with anticipated North American supplies of these materials. (For the purpose of establishing stockpile goals, defense and civilian investment demands are to be supplied from North American sources; whereas other civilian uses can tap whatever remaining sources are available.)

The principal planning factor assumptions are summarized in Table II-1. Eleven areas are shown. The assumptions provided have formed the basis for stockpile requirements estimates since the 1989 report to Congress.[1] Most classified assumptions are contained in the Secretary of Defense's report to Congress on NDS requirements.[2]

B. PLANNING SCENARIO DEMAND PROJECTIONS

Almost all of the germanium (Ge) consumed by the military at present is incorporated in infrared (IR) imaging equipment used for radars, night vision devices, navigational systems, and similar applications. Nearly all of the aircraft in the military inventory are now fitted with at least one Ge-containing IR system, and many have several.

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1 James S. Thomason, et al, *National Defense Stockpile Program Phase I: Development and Analyses*, IDA Paper P-2314, March 1990. The table of assumptions appears on page III-3. It is assumed new capacity can be added during the warning year, whereas the earlier study assumed only existing capacity would be available.

2 The *Report of the Secretary of Defense to the Congress on National Defense Stockpile Requirements*, 1989.

Table II-1. Stockpile Planning Assumptions

PLANNING FACTOR	1989 PRINCIPAL ASSUMPTIONS
Nature of Emergency	Major conventional conflict with the Soviet Union and its allies in late 1989
Duration and Warning	1 year warning; a few months of initial conflict followed by stalemate and two plus years of emergency build-up leading to *second conflict*
Intensity of Conflict	Intense, multi-theater conflict followed by stalemate and major force rebuilding effort
U.S. Force-Building Targets	Replace losses from initial conflict and expand to planning force levels, including 6 months of sustainability
Support of Allied Force-Building Goals	General support but no explicit U.S. production to rebuild allied losses
Civil Sector Demands	Consumer durables, residential investment and general non-residential investment decrement based on consensus among civil agencies
War Damage	Classified
Trade Conditions (General)	Exports reduced across-the-board 50%; imports reduced an average of 30% due to war damage, shipping losses and reliability
Shipping Losses	Classified
Strategic and Critical Material Supply Availability	Assured suppliers: Canada, Mexico, (and U.S.) (existing facilities only) Reliable foreign suppliers: Classified; (existing facilities only)
General U.S. Production Conditions	
• Production Process Times	75% of Peacetime
• Shifts	3-8-5 (3 eight-hour shifts, 5 days/week)
• Time to Build New Plants	12-month average
• Time to Hire and Train New Workers	3-month average

The Army's tanks and Bradley vehicles are fitted with IR devices for navigation and targeting. All of the Army and Marine Corps anti-tank battalions include platoons armed with TOW missile systems, which are controlled with Ge-containing IR devices. TOW systems are also installed in many combat helicopters, including the Apache. The Navy has also fitted its aircraft with IR devices and is now experimenting with IR systems on some of its ships.

The typical IR device has an external window and several internal lenses made of high-purity intrinsic Ge. These elements vary widely in size and number so that IR systems also vary widely in the total Ge they contain.[3] Some use as little as 10 ounces of Ge, while others require as much as 15 or 16 pounds. Emergency Ge requirements thus depend on the following factors:

1. The mix and number of aircraft, tanks, etc., produced during the crisis, and the number and types of IR devices installed in them.
2. The level of IR replacement requirements generated during the conflict by wear and tear, damages sustained in operations, and system modifications dictated by operational experience.[4]

It is worth noting, however, that aircraft, ships, land vehicles, and anti-tank battalions not deployed to combat zones do not have the same need for installed IR devices as units deployed to regions where there is the prospect of combat. Since IR devices are detachable, they can be moved from one vehicle to another if necessary.

This study team developed a comprehensive database of military IR systems and their Ge content (see Section B, below) as a basis for estimating emergency Ge requirements (see Section C). The authors bring the supply and requirements pictures together in Chapter IV of this paper to assess the policy of the National Defense Stockpile (NDS) in regard to Ge.

A comprehensive list of IR systems employed by the armed forces was obtained from the various Service program offices. This list included, in most cases, the identities of the contractors producing the systems. The contractors were then contacted to obtain estimates of the Ge contained in each system. Similar information was obtained from the

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3 In general, it can be assumed that about 40 percent of the Ge in an IR system is accounted for by the window. Some systems have very large windows and small internal lenses.

4 Modifications are already being made in the IR devices controlling the TOW missile as a result of the Desert Shield experience.

Army's Night Vision Center for Army IR systems, which provided an important quality check for data obtained from contractors. This undertaking proved to be difficult because a surprisingly large number of contractors (and program offices) do not develop data on the materials content of the systems they produce.

At any given time, there are IR systems ranging from those under development to those developed and funded for purchase by the Services. Some of the former will never be funded. Some of the latter are obsolete and will be dropped from the inventory as replacement systems become available. In between there is a class of systems that are more or less fully developed but as yet unfunded for procurement by the Services. It is important to keep these distinctions in mind. Failure to do so can lead to serious over-estimation of emergency Ge requirements. Following the Office of the Secretary of Defense (OSD) policy. In the estimates prepared for this study, only funded program requirements have been considered.

It was not possible to obtain Ge content estimates for all IR systems. A few contractors were uncooperative. In these cases, the authors estimated Ge requirements by using the data obtained for similar IR systems produced by other contractors. The error introduced by this procedure is unlikely to be significant since the researchers were able to obtain contractor data for all of the high-volume IR systems currently in use.

Table II-2 summarizes the database developed as part of this study. The third column in this table identifies the IR device, and the second column identifies the weapons system in which the IR device is installed. The sixth column indicates the Ge contained in each IR device, while the fifth column estimates the total number of such devices that would be manufactured during the assumed emergency scenario. The seventh column estimates the total Ge required for IR devices for the units to be produced.

In most cases the authors received from the contractors a high and low range of Ge unit content estimates rather than point estimates. In all but one or two cases, they used the upper end of these range estimates for the data reported in Column 6 of Table II-2. This maintains the methodological thrust of this study: assessment of Ge requirements on the basis of "high side" requirements estimates.

Table II-2. Estimated Germanium Requirements for the 3-Year War Scenario

Service	Weapon	Device	Type	Demand Units	Max Ge Content (lb)	Total Ge Required (lb)
Army	UH-60A	AN/AAQ-16	FLIR	351	5	1,755
Army	AH-64	TADS/PVNS	FLIR	1,259	20	25,180
Army	OH-58D	MMS	FLIR	1,000	7	7,000
Army	M1	AN/VAS-3	FLIR	2,886	7	20,202
Army	M2	AN/VAS-3	FLIR	5,239	1.5	8,068
Army	M113	AN/UAS-11	FLIR	19,017	1.5	28,525
Army	LOW COST	RIFLE SIGHT		30,000		27,550
Army	TOW	AN/TAS-4	SIGHT	4,452	0.7	3,116
Army	TOW	AN/VAS-12	SIGHT	4,452	0.7	3,116
Navy	A-6E	AN/AAS-33	FLIR	107	9.6	1,027
Navy	EA-6B	AN/AAS-33	FLIR	53	9.6	509
Navy	AV-8B		IR TEL.	30	0.7	21
Navy	F-14A/D	AN/AAS-42	IRST	142	20.0	2,840
Navy	F/A-18	AN/AAS-38A	FLIR	267	10.0	5,340
Navy	CH-53E	AN/AAQ-10	FLIR	68	6.6	449
Navy	AH-1T	AN/AAS-32	FLIR	33	5.5	181
Navy	SH-60B	AN/AAQ-16	FLIR	25	5.0	125
Navy	LAMPS/ASW	AN/ALQ-142	FLIR	72	5.0	360
Navy	P-3C	AN/AAS-36	FLIR	108	10.6	1,145
Navy	E-2C	ACR-73	FLIR	28	10.6	297
Navy	AIM-9		SEEKER	15,817	0.7	11,072
Navy	AMRAAM		SEEKER	2,884	0.7	2,019
Navy	HARPOON		FLIR	7,014	0.7	4,910
Navy	IIR MAVERICK		SEEKER	4,567	0.7	3,197
Navy	DDG-51 (ETC.)		IRST	219	8.0	1,752
Navy	FFG-7		FLIR	100	7.3	730
AF	A-10A	AN/AAR-42	FLIR	799	15.0	11,985
AF	F-15E	AN/AAQ-13	FLIR	796	15.0	11,940
AF	F-16C/D	AN/AAQ-13	FLIR	1,444	15.0	21,660
AF	MC-130H	AN/AAQ-9	FLIR	4	6.6	26
AF	E-3A		FLIR	25	8.0	200
AF	C130H	AN/AAS-36	FLIR	293	10.6	3,106
AF	H/H-60D	AN/AAQ-15	FLIR	18	5.0	90
AF	SIDEWINDER		SEEKER	7,049	0.7	4,934
AF	IIR MAVERICK		SEEKER	2,879	0.7	2,015
AF	AMRAAM		SEEKER	13,640	0.7	9,548
	Total High Side Estimates					225,990
	Replacement IR Elements (+25%):					56,497
Total						282,487

The JIMPP Model aggregates replacement parts and components into several "basket" categories that are not useful for assessing the Ge requirement for replacement parts and components. This requirement cannot be ignored, however, because IR systems are inherently fragile, especially those mounted in tanks and aircraft. The study team was unable to locate Service data on replacement demand and was forced to estimate this requirement. This was done simply by assuming that 3-year replacement component Ge requirements would equal 25 percent of the total Ge content generated by system-by-system estimates summarized in Table II-2. This expedient generates an incremental requirement for 25.6 MT of Ge. If it is assumed that the average IR device contains 8 pounds of Ge, the incremental requirement equates to 7,062 complete IR devices. If it is also assumed that the average IR device contains 4 optical elements made of Ge, this implies a requirement for approximately 1.5 months of mobilization capacity in the infrared sector of the precision optics industry as estimated by the JPOG survey--that is if all of the IR element capacity estimated in the JPOG survey is for Ge elements; it may not be. Interested readers, of course, can substitute their own judgments on this matter.

Excluding replacement demand, total Ge requirements generated in Table II-2 come to 102.5 MT for the 3-year emergency scenario, or 34.2 MT/yr. This compares with total 1989 defense sector IR Ge consumption, as estimated by the Bureau of Mines and Roskill, of approximately 21 MT (see Chapter I). Including replacement demand, this total rises to 128.1 MT, or 42.7 MT/yr. This figure represents a doubling of the current level of Ge requirements for defense-related IR device production. Assuming again that the average IR device contains 8 pounds of Ge and 4 optical elements made of Ge, this total Ge requirement implies approximately 8 full months of infrared optical capacity for the Ge elements alone. It is, therefore, a feasible program provided that the 1985 IR precision optics unit capacity estimates remain accurate. Serious additional erosion of the industrial base in this sector could undermine the plausibility of this study's estimates.

In evaluating this study's estimate, it is important to bear in mind that the base year to which the estimate has been compared, 1989, was not a year of depressed IR device production. The armed forces have been investing substantial resources recently in equipping their aircraft , ground vehicles, and anti-tank forces with IR systems, especially night vision equipment. A doubling of average annual Ge input to IR device production therefore represents a substantial increase in IR system production.

C. TECHNOLOGICAL TRENDS

Looking to the future, it is likely that technological developments over the next 5 years will improve the life expectancy of IR systems in service and reduce the quantity of Ge required per system. While it is impossible to attach numbers to these trends at the present time, it is clear that the overall direction of change in military IR Ge requirements is down, not up. There are many problems with present-day IR systems, however, and DoD is funding substantial research that will improve IR performance, and as a result reduce requirements for germanium. The main areas of R&D effort are the following:

1. Development of more efficient detectors. This work does not involve Ge and will not, therefore, be discussed here.
2. Reduction of the vulnerability of IR windows to environmental hazards such as shock, salt water, and wind-blown sand. Most of the work in this area involves development of hard exterior coating materials that will protect Ge windows but not adversely affect their optical performance. The most promising possibility under investigation is to coat the windows with a thin film of diamond. Industry experts believe that a useful product employing this technology will become available in 2 to 3 years.
3. Integration of IR and visible detection systems. Partly for budget reasons, the armed forces are assigning a high priority to developing dual-purpose optics integrating IR and visible frequency sensors in the same instrument.[5] Since Ge is opaque to the visible light frequencies, integrated systems will require external windows fabricated from materials other than Ge.[6] A related line of R&D involves using various reflector mirrors in place of some of the lenses contained in present-day IR devices. Industry experts indicate that it should be possible to reduce the number of lenses in IR devices by 25 to 50 percent, with proportionate decreases in the amount of Ge required per system.[7] Reflective mirrors are now being worked with using glass, aluminum, and beryllium.

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5 A mutli-spectrum, dual-purpose sensor system has already been developed and tested for the LHX helicopter.

6 See Anthony Owen, "Taking Advantage of Reflective Optics for the Infrared," *Photonics Spectra*, September 1990.

7 Telephone interview with Mr. Thomas Neff, II-VI, Inc., 25 September 1990. II-VI is a major producer of optical elements.

Companies working in this area include: Kollmorgan Inc., Martin Marietta, Hughes Aircraft, Raytheon, and McDonnell Douglas.

4. Substitution of other materials for Ge in the fabrication of IR windows and/or lenses. There are other materials that can perform the optical functions of Ge. None that has been found to date, however, is as efficient as Ge in the critically important 8 to 12 micron IR range.

Aviation and precision optics authorities already recognize that the Ge external windows in IR systems installed on high-speed aircraft and missiles will have to be replaced with windows made of a material that does not degrade optically, as Ge does, at 100 degrees centigrade.[8] At the present time, this appears to be zinc sulfide (ZnS) or zinc selenide (ZnSe).[9] Assuming that the exterior windows account for approximately 40 percent of the Ge contained in the relevant sensors, this means that substitution of ZnS, ZnSe, or some other material for Ge in the fabrication of FLIR systems for the high-speed aircraft and missiles in Table III-1, above, would eliminate approximately 13 percent of total emergency military demand for Ge.

The trend towards multi-spectral systems (visual and IR optical trains in the same sensor system) is a more serious threat to Ge's long-term IR market. Since Ge is opaque to visible light, dual-purpose IR systems would have to feature windows made of some other material. Unless DoD funding for advanced IR system R&D is reduced drastically in the next 5 years, it is likely that dual-purpose systems will soon begin to reduce emergency military requirements for Ge since they would have advantages for nearly every weapons platform on which IR systems are installed.

There is a related technological development that also indicates reduced Ge requirements: introduction of staring focal plane detectors in IR systems. These sensors do not require the same degree of IR signal refocusing that is necessary with detectors used in the past. This has the potential of reducing the number of Ge lenses required in the interior optical trains of IR systems and encouraging the use of more interior reflectors.

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8 Telephone interview with Dr. William Cooper, Manager of New Business Development, Pacific Optical Division, Recon Optical Inc., 13 November 1990. Pacific Optical is a prominent manufacturer of IR windows, lenses, and forward-looking infrared (FLIR) systems.

9 This is not an unmixed blessing. There is only one U.S. supplier of IR-grade ZnS and ZnSe: Morton International (MI), a division of Morton Thiokol. MI owns and operates a plant that was once a division of Raytheon but was "spun off" several years ago. According to Dr. Cooper of Pacific Optical, lead times on ZnS/ZnSe orders to MI currently run from 16 to 20 weeks.

D. RECYCLING

Another factor that will substantially influence military requirements for germanium is the degree of recycling. A strong case can be made for encouraging the armed forces to recycle damaged IR windows and lenses made of Ge as an alternative to buying more Ge for the NDS. Recycled Ge replaces virgin source materials almost ton for ton and thus economizes on consumption of this scarce natural resource while rendering the United States less dependent on imports. Purchase of Ge for the NDS provides only a momentary stimulus to the Ge industry, much of it likely to be of benefit to foreign rather than domestic firms. In contrast, a comprehensive recycling program would help sustain a vigorous domestic industry engaged in producing and refinishing IR windows and lenses and remelting elements that cannot be refinished.

According to Exotic Materials Inc. (EMI),[10] the Air Force has recycled IR windows from its B-52 community for years, and the Army has sporadically recycled IR elements from its Abrams tank and Apache helicopter communities. To EMI's knowledge, however, no IR elements have been recycled from other Air Force and Army weapons communities or from any of the Navy's weapons communities. This is surprising since the Army's large fleet of Bradley vehicles is fitted with FLIR systems containing Ge windows and lenses, while many Navy and Marine Corps aircraft are also equipped with IR systems. Given present technology, the turnover of IR elements in Navy aircraft-mounted IR systems must be high, especially for aircraft operating off carriers.

A warehouse on the Jacksonville Naval Air Station, Jacksonville, FL, currently holds an inventory of Ge scrap of about 2.3 MT.[11] Most of this material consists of windows from Navy aircraft IR systems, but there is also some scrap from Air Force and Army sources. According to NAVAIR, the Navy has been unable to dispose of this material because some of it has a toxic thorium fluoride coating.[12] The Army Depot, Sacramento, CA, which is on the list of military facilities to be closed, has an optical element refurbishing facility to which repairable IR elements are sent for refinishing and

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[10] Telephone interview with Mr. Richard Sharman, President, EMI, 2 October 1990. Eagle-Picher Industries and Cabot are also capable of recycling scrap Ge. Eagle-Picher manufactures optical blanks as well.

[11] Telephone interview with Mr. Joe Kunda, Naval Air Systems Command, Code Air-41213C, Washington, D.C., 14 November 1990.

[12] Note, however, that Amorphous Materials, Inc., Fort Worth, TX, has made an offer for this scrap.

subsequent re-issue. This facility may also have some scrap Ge, but the quantity involved is not large.[13]

Accumulation of an inventory of quality Ge scrap may provide a cost-effective substitute for stockpiling virgin germanium. The authors recommend that a study be conducted to assess the economics of IR device recycling on a Service-by-Service basis and that proposals be developed for recycling systems if the economics of recycling are favorable.

[13] Telephone interview with Mr. Clark Winter, Army Material Command, Washington, D.C., 14 November 1990.

III. ESSENTIAL CIVILIAN APPLICATIONS OF GERMANIUM

Table I-4 in Chapter I presents data on U.S. consumption of Ge by end-use category.[1] Table III-1, below, regroups these data to isolate trends in military versus civilian consumption. Note in Table III-1 that military consumption grew from 43 percent of total U.S. consumption in 1980 to 64 percent in 1989. When the data for 1990 become available, they are likely to reveal further erosion of the civilian market for Ge.[2] Table III-1 also shows that the absolute level of civilian Ge consumption has declined by 43 percent since its peak in 1982. In fact, civilian consumption has declined steadily since 1982. Military consumption, on the other hand, has grown steadily, primarily because of the demand for IR systems.

All major categories of consumption except for IR systems have participated in the decline of the civilian Ge market, but the decline has been most severe in semiconductor applications. The reason for this decline was noted in a previous section of this report: Ge has lost market position to substitute materials. In semiconductors, the loss has been mainly to silicon. The displacement of domestic semiconductor fabrication by imports has also played a role in suppressing the domestic market for Ge, but the replacement of Ge with other materials has taken place abroad as well. In detectors, Ge has been replaced by gallium arsenide, cadmium mercury telluride, and various other sensor materials containing gallium, indium, zinc, and related materials. In most cases, detector markets have been lost

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1 The reader is advised not to place heavy confidence in published data on Ge consumption. As in the case of other small industries, the Ge industry is not well documented statistically. The data in Table I-4 were developed by Roskill in the context of an extensive annual survey of Ge and are probably the most accurate data available. The Roskill data are consistent with Bureau of Mines (BoM) estimates. They are probably more useful as measures of changes over a period of years than as indicators of year-to-year consumption changes.

2 The authors calculated the data in Table III-1 on the basis of the following assumptions:

- That 92 percent of total infrared consumption is accounted for by the military market.
- That 10 percent of total U.S. non-infrared consumption is military

The first assumption is derived from IR systems manufacturers and should be accurate. The second assumption is based on this study's analyses but is also considered reasonable by the U.S. Bureau of Mines Ge specialist; telephone interview with Mr. Thomas Llewelyn, U.S. Bureau of Mines, 25 October 1990.

to materials that are superior in terms of cost and performance. Additional consumption has been lost to the miniaturization trend observable in most electronics markets.

Table III-1. Relative Importance of the Military and Civilian Markets for Germanium

Year	Ge Consumption (MT)				Military Consumption as % of Total
	Total	Military		Civilian	
		IR	Non-IR		
1989	36	21.5	1.5	13.0	64%
1988	40	24.7	1.5	13.8	65
1987	40	23.9	1.6	14.5	64
1986	38	20.9	1.7	15.4	59
1985	38	20.9	1.7	15.4	59
1984	35	19.3	1.6	14.1	60
1983	38	16.1	1.9	17.0	51
1982	42	16.6	2.5	22.9	45
1981	38	14.0	2.4	21.6	43
1980	32	11.8	2.0	18.1	43

Clearly, in most categories of consumption U.S. civilian demand is either declining or stagnant. Table III-1 also shows that the military market now accounts for nearly two-thirds of total U.S. Ge consumption.

The balance of Chapter III addresses the major civilian sector applications of Ge individually to isolate those applications to be considered "essential" for mobilization purposes.

A. PRINCIPAL CIVILIAN APPLICATIONS OF GERMANIUM

1. Optical Fibers

Ge is used as a dopant in the manufacture of optical fibers to improve the index of refraction of the fibers. The market is mainly for long-distance fiber optic systems.[3] Demand for Ge in this application grew rapidly until 1981-82 and then declined because of

[3] Telephone interview with Dr. W. P. Siegmund, Schott Fiber Optics, 26 September 1990.

the introduction of thinner fibers requiring much less Ge dopant per line-mile of cable,[4] and because of improvements in the doping process.[5]

Optical fiber systems in most cases replace copper systems already in place. While they vastly expand the capacity of the systems, they do not usually involve extension of essential telecommunications services to consumers previously lacking such services.[6] This is one reason why the growth of demand for fiber optic systems has not fulfilled expectations in recent years. The authors conclude, therefore, that civilian optical fiber demand does not generate an essential mobilization requirement for Ge except in respect to system maintenance requirements, which IDA estimates at about 20 percent of current annual Ge consumption in optical fibers. This amounts to about 0.5 MT of Ge per year. Other civilian applications of Ge-containing optical fiber are postponable and therefore non-essential from the national security perspective.

The authors note incidentally the fact that considerable research effort is being devoted to development of optical fiber that will not require Ge doping, even for long distance telecommunications applications. A Japanese company recently announced its readiness to market such a fiber, but American experts contend that the product has serious problems and is not yet in production.[7]

2. Catalysts

Ge-containing catalysts constitute an important market for Ge in Europe and Japan, where a Ge catalyst is widely used in the production of polyethylene terephthalate (PET) plastic bottles for food packaging. This application is, in fact, the most important Ge market in Europe and Japan. In the United States, however, an antimony catalyst is used

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4 "Update to the International Competitiveness Study of the Fiber Optics Industry," U.S. Department of Commerce, 1 May 1989, Washington, DC. See also Roskill, pp. 117-136.

5 At the outset, only 5 percent of the Ge used in doping optical fiber was actually deposited on the glass. The rest was lost. After introduction of the plasma process, the deposit rate rose to 45 percent. About 10 to 15 percent of the optical fiber produced does not pass inspection. Therefore, yields are still only 38 to 40 percent. None of the lost Ge or the Ge contained in rejected optical fiber is recycled. Telephone interview with Mr. Jack Adams, Eagle-Picher, 29 August 1990.

6 This is the main reason why this study does not consider trans-oceanic fiber optic cables to constitute an essential civilian application of Ge. Trans-oceanic fiber optic cables merely replace existing copper cables, to be sure vastly expanding capacity in the process. Furthermore, it is unlikely that laying trans-oceanic fiber optic cable would be considered a profitable (or healthy) enterprise during periods of mobilization for global war.

7 Telephone interview with Mr. Dale R. Niebur, Product Engineer, Corning Glass Telecommunications Products Div., 21 October 1990.

for this purpose. In the past, some Ge was also used as a catalyst in petrochemicals production other than PET, but there is no evidence of its continued use in this application.

Englehard Metals and a Japanese firm are said to be developing a germanium dioxide catalyst for use in automotive catalytic converters to remove nickel from engine emissions. The auto emissions regulations in the United States, however, do not require nickel removal. Thus, American automakers would require the catalyst only for export vehicles. Note, in any case, that the dioxide is not yet being offered in the market as a catalytic converter additive.[8]

The authors conclude that there are no essential civilian applications for Ge catalysts at this time.

3. Semiconductors

The dominant world producer of Ge semiconductors is an American company, Germanium Power Devices Corporation (GPDC). Much of the discussion in this section derives from information provided by GPDC.

While the invention of Ge transistors triggered the massive growth of post-World War II electronics, Ge has largely lost this market to cheaper and more efficient materials. In diodes, rectifiers, power diodes, and high frequency detectors, for example, Ge has been replaced by silicon, which has electronic properties similar to those of Ge but costs much less. Ge is still used as a dopant in the manufacture of tunnel diodes, but the volume of Ge required is small.

Use of Ge in transistors continues but, again, not in large volumes. The main remaining markets are in specialized transistors such as field effect transistors (FETs).

In the past, considerable volumes of single crystal Ge wafers were used as substrates for gallium arsenide light emitting diodes (LEDs). Ge, however, does not produce as intense a light as gallium and this, couples with the cost of Ge, has resulted in its loss of this market.

The extent to which Ge has been displaced from the semiconductor market was estimated by Roskill using data published by the Japanese government. These data indicate that total Japanese consumption of Ge in semiconductors declined from 20 MTper year in

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8 Industry experts speculate that total demand for Ge as an automotive catalytic converter additive could reach 5 to 10 MT/yr on a metal content basis.

the early 1970s to only 1.1 MT in 1986.[9] Consumption in the United States remains somewhat higher because of the market position commanded by GPDC. But even GPDC executives project little or no future growth in this market barring unexpected technological developments.

There is no convenient way to assess the essentialness of what remains of the semiconductor market for Ge. Consequently, the authors assume that all of the 1989 Ge consumption in this application represents essential demand but that there will be no growth in the market. Mobilization requirements, therefore, are estimated at approximately 2.9 MT per year. This is certain to exaggerate essential requirements because of the availability of satisfactory substitutes.

4. Superconductors

Superconducting materials are metals, compounds, alloys, oxides, organic compounds, and ceramics which lose their electrical resistance when cooled below some critical temperature known as the "superconducting transition temperature."[10] The potential military and civilian applications of superconductivity are such that every major industrial country is investing in substantial R&D to develop superconductor technology. Unfortunately, the critical transition temperatures thus far achieved in superconducting materials remain very low. This is a barrier to commercialization because superconductivity disappears rapidly at temperatures above the critical transition temperature for a material. This means that the phenomenon remains very expensive to produce as superconducting devices must be kept very cold. Furthermore, the superconducting materials studied to date are difficult to fabricate to useful shapes such as wires, cables, flats, and tubes.

While some Ge is being used in current superconductivity R&D, there is no guarantee that it will be used in practical applications of the technology. Recent advances in the development of ceramic and organic superconductors suggests that this may not, in the long run, become a significant market for Ge. In the meantime, the amount of Ge being used for superconductor R&D is very small--probably less than 100 kilograms per year.

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9 *The Economics of Germanium 1990*, Sixth Edition. Roskill Information Services Ltd, London, England, p. 141.

10 N. D. Jorstad, *Bounding an Emerging Technology: Superconductivity*, IDA Paper P-2211, Institute for Defense Analyses, Alexandria, VA, December 1989, p. H-7. This study presents a comprehensive summary of the potential applications for superconductors.

The authors conclude, then, that there is no demonstrable emergency requirement for Ge in superconductors in either the civilian or the military sectors. As in the case of other advanced materials, however, the implications of future progress in superconductors for Ge requirements should be monitored on an annual basis.

5. Phosphors

There are Ge compounds (e.g., magnesium germanate) that are luminescent and therefore useful in fluorescent lights of various kinds. There are cheaper substitutes, however, and demand for Ge in this application is declining. In Japan, for example, the phosphor market now consumes less than 100 kilograms of Ge per year, according to Roskill. There is no phosphor application of Ge in the United States that consumes significant quantities of Ge.

Fluorescent lights are not, in any case, an essential application of Ge. The authors conclude, therefore, that there are no essential applications of Ge in the phosphor market that need to be considered in estimating total emergency requirements for Ge.

6. Infrared Systems

Although aggregate demand for Ge in infrared applications remains overwhelmingly military, there are some important and growing civilian applications of the technology. The main ones include--

- Night vision equipment in civilian aircraft and ships.
- Inspection equipment to detect faults in metal components and joints.
- Night vision equipment for security systems, fire alarms, and various police applications.
- Forest fire detectors and search equipment for fire fighters.
- Safety equipment in coal mines.
- Laboratory equipment.

Ge requirements in these applications are not well documented in the technical and marketing literature on Ge. Roskill and others, however, estimate that approximately 10 percent of total IR systems Ge demand in the United States is accounted for by civilian applications. This estimate is very rough at best, but it is useful because the numbers involved are not large. Applied to the 1989 data, this estimate generates a total of about 2.5 MT of Ge demand in the production of civilian IR systems. Much of this demand is clearly

postponable, however, and unlikely to constitute a priority application for scarce Ge supplies during an emergency.

For present purposes, this study estimates that 50 percent of civilian IR systems demand is essential. Given that assumption, approximately 1.25 MT of Ge would have satisfied essential civilian requirements in 1989. But civilian applications of IR systems are expanding rapidly, although no one seems to have good estimates of how much Ge is involved. To allow for growth in essential requirements, the authors assume that total requirements will reach approximately 2 MT per year by the mid- to late-1990s.[11] These estimates are very subjective, however, and do not take into consideration many relevant factors such as the availability of substitute materials and differences of opinion as to what is essential and what is not.

B. OTHER APPLICATIONS

There are many other applications of Ge in small quantities, some of which may become significant future markets. It is impossible to consider them all in this report. The more important or interesting of these applications are listed below. Most of these applications are either non-essential or in areas currently subject to technological instability.

- Radiation detectors for gamma and X-ray radiation.
- Nuclear power plants, gamma-ray scanning in medicine, environmental control in oilfields, and physics research. The annual Ge requirement for these applications is no more than a few hundred kilograms.
- Lasers and light detectors, especially in fiber optic systems and in optical disk technologies. The trend, however, is toward other materials, in particular GaAs and In GaAsP.
- Thermoelectric devices. This is mainly a small semiconductor market in which there is little growth at the present time.
- Solar cells, mainly for space applications. This is a "high tech" application that may some day have terrestrial applications if costs can be reduced and conversion efficiencies improved.
- Metallurgical applications. Considerable research has been conducted on various alloys incorporating Ge. While interesting results have been achieved

[11] This estimate is based on the assumption that essential civilian IR systems demand for Ge will grow at roughly 10 percent annually from the base-year (1989) level of 1.25 MT/yr. This is considered a "high side" estimate because civilian IR technology is subject to the same technological trends as is military IR technology.

in some cases, the high cost of Ge has prevented commercial applications of any significance to date.

- Medical. Ge is used medicinally in some countries, but not in the United States. This application could disappear soon because recent research indicates that medicinal Ge may have adverse long-term effects. The UK Department of Health, for example, has warned consumers not to use health products containing Ge.

C. SUMMARY

The above discussion indicates that there are many civilian applications for Ge but that significant volumes are involved only in optical fiber and infrared systems production. The analysis also reveals that most civilian applications are postponable in the sense that unavailability of Ge during periods of national emergency would impose no significant hardship on the public or on the industrial sector. Finally, it has also been shown that the availability of substitutes is a competitive reality for Ge in almost all of its markets.

The authors estimate essential civilian requirements as follows:

Optical fiber		0.5 MT per year
Semiconductors		2.9 MT per year
IR systems		2.0 MT per year
	Total	5.4 MT per year

The optical fiber producers buy Ge in the form of the tetrachloride, which is a precursor in the production of metallic Ge. Semiconductor demand is primarily for high purity polycrystalline Ge, as is also the demand in IR systems.

It is to be emphasized that the above estimates are crude and based on a problematical database. Furthermore, there are differences of opinion as to how essential are many of the applications considered in this study. There are engineers and scientists, for example, who argue that Ge is no longer an essential material for any important semiconductor application. On the other hand, there are also industry experts who believe that optical fiber requirements for Ge are essential.

Two conclusions emerge from the analysis with clarity. First, total civilian Ge consumption has declined steadily since 1982 (Figure I-3 and Table III-1, above). There is no reason to anticipate a reversal of this trend any time soon. On the contrary, technologies now using Ge represent one of the most dynamic markets in the modern economy. These markets teem with R&D, much of it focused on substitute materials and on system

innovations that will reduce per unit requirements of expensive scarce materials like Ge. Second, there is no essential civilian application of Ge in which sharp increases in Ge requirements are likely in the event of an emergency.

Note that this study's estimate of total essential civilian requirements for the 1990s, 5.4 MT per year, is about 41 percent of total civilian consumption in 1989. It is not, therefore, a conservative estimate.

IV. GERMANIUM REQUIREMENTS AND SUPPLY FOR THE NDS PLANNING SCENARIO

Estimates of demand and supply of germanium for a major national emergency provide the basis for sizing the germanium stockpile. Using the planning parameters for the National Defense Stockpile, we find that germanium consumption would increase from the current rate of 36 MT per year to an estimated 48 MT per year in the scenario war years (Table IV-1). Military consumption nearly doubles, from 23 MT per year to 42.7 MT per year. Civilian use drops sharply, however, because most civilian use is not considered "essential" for the purpose of calculating stockpile goals.

Table IV-1. Germanium Supply and Demand for NDS Planning

(Metric Tons)

		Scenario War Years		
	Current	1	2	3
Demand				
Civilian [a]	13	5.4	5.4	5.4
Military	23	42.7	42.7	42.7
Total	36	48.1	48.1	48.1
North American Supply				
Mining [b]	30	70+	70+	70+
Extraction [c]	6	70+	70+	70+
Refining	36	100+	100+	100+
Total (Limited by Extraction Bottleneck)	-	70	70	70
Net Supply	-	21.9	21.9	21.9

a Essential civilian uses included in war years.

b Feedstock of low-concentrate germanium is more than ample from zinc mining and from existing mine residue piles.

c Assumes restart of Hecla extraction facility and construction of a 30 MT per year extraction facility during the warning year.

Ample supplies to meet this 33 percent increase in germanium demand are available in Canada and the United States, provided that zinc mining continues and that steps are taken during the warning year to augment some phases of domestic germanium processing capacity. The supply process for germanium entails three main phases: 1) zinc mining and smelting, which yields germanium in trace amounts of less than 1 percent in the smelter residues; 2) extraction, which concentrates the germanium in these residues to levels of 20 percent or more; and 3) refining, which creates high-purity germanium through a series of chemical and heat-treating process. The main bottleneck in expanding production to meet the scenario requirements lies in the limited capacity for extraction, because little extraction is done within North America today. If domestic extraction capacity is increased during the warning year to match current zinc smelting output--a readily feasible option--domestic supplies will exceed demand in each of the three war years.

In interpreting these estimates, readers should be reminded that weapon system production lead times will have an important impact on war scenario Ge requirements. If there is insufficient peacetime demand to keep production lines open, the time required to produce the quantity of equipment identified in this analysis will stretch out dramatically. Consider, for example, what has happened in the case of the Navy's P-3 Orion. The Orion production line was shut down years ago and is now in poor condition. Navy experts estimate that restoration of the production line would take 2 years and that the first new Orion off the line could not be expected in less than 4 to 5 years. This example suggests that in many warfare areas, the demand for germanium in the three scenario years may be confined mainly to replacement devices and elements. This obviously would decrease wartime demand substantially below the levels calculated in this report.

There are three possible future developments, discussed in earlier chapters, that also may alter the supply and demand conditions relative to the estimates presented here. First, germanium processing capacity is highly concentrated in a handful of firms, so North American capacity could change quickly if firms enter or exit the industry. There are only three primary materials producers. Loss of either the Trail smelter in British Columbia or the Clarksville smelter in Tennessee would fundamentally alter the primary Ge feedstock availability picture developed in this study. Similarly, refinery capacity is dominated by a single firm, Eagle-Picher. Loss of this firm's capacity would be especially serious because, in addition to accounting for a large share of total U.S. Ge refining capacity, it is also a major producer of blanks and substrates. Equally important, Eagle-Picher is considered by IR element manufacturers to produce the highest quality intrinsic Ge bars

and ingots available in the United States. In summary, the availability situation documented in this study is vulnerable and should be monitored regularly by defense planners.

Second, technological change may reduce the military's reliance on germanium for infrared devices. As noted earlier in the text, germanium requirements for semiconductor electronics devices have been falling for some years. In addition, DoD is funding substantial research to improve night-vision performance, which will also reduce demands for germanium. This research promises to improve the durability of germanium windows through the use of harder coatings. It also may lead to the use of alternative substances for infrared windows and lenses. Hence, in the long-run, the importance of germanium is likely to decline, and stockpile requirements should be reviewed as this trend progresses.

Third, more systematic recycling of the germanium contained in surplus or damaged infrared devices could provide a cost-effective substitute for stockpiling virgin germanium. This study assumes no recycled materials are available for meeting military and essential civilian requirements. The availability of such materials would augment germanium extraction and refining capacity. Indeed an important corollary finding of this study is that DoD should examine the possibility of expanding recycling programs beyond those in operation today.

The National Defense Stockpile has a germanium inventory of about 68 MT--more than one-year's wartime consumption in the stockpile scenario. Moreover, the estimated supply assumptions for this analysis are understated. So long as the current producers maintain their germanium capacity, the factors discussed above err in the direction of overestimating germanium stockpile requirements. Hence, the current inventory should be ample to meet any shortage that may develop while domestic processing capability is being expanded, and to hedge against uncertainty. This study concludes, therefore, that there is no need to buy additional germanium for the National Defense Stockpile.

Appendix A

COMMON OPTICAL MATERIALS FOR THE INFRARED (U)

Appendix A
COMMON OPTICAL MATERIALS FOR THE INFRARED

MATERIALS	REFRACTIVE 4mm	INDEX 10mm	dn/dt (/DEG C)	COMMENTS
Germanium	4.0243	4.0032	0.000396	Expensive, large dn/dt
Silicon	3.4255	3.4179**	0.000150	Large dn/dt
Zinc Sulfide (CVD)	2.2520	2.2005	0.0000433	
Zinc Selenide (CVD)	2.4331	2.4065	0.000060	Expensive, very low absorption
AMITIR/(Ge/As/ Se: 33/12/55)	2.5141	2.4976	0.000072	
Magnesium	1.3526	______*	0.000020	Low cost, no ctg. req., high scatter
Sapphire	1.6753	______*	0.00001	Very hard, low emissivity at high temp
Arsenic Trisulfide	2.4112	2.3816	***	
Calcium Fluoride	1.4097	______*	0.000011	
Barium Fluoride	1.4580	______*	-0.000016	

* Does Not Transmit
** Not Recommended
*** Not Available

Source: R.E. Fischer, "IR System Design: the Basics," Photonics Design on Applications Hardbook, p. H-183. Lauria Publishing Co., Pittsfield, MA 1990.

Appendix B

COMPANIES AND INSTITUTION CONSULTED (U)

Appendix B
COMPANIES AND INSTITUTIONS CONSULTED

APPLIED SOLAR ENERGY, INC. Manufacturer of Ga/Ge solar cells	213-968-6581
ATOMERGIC CHEMETALS CORP, Farmingdale, N.Y. Manufacturer of single crystal Ge and other materials	516-694-9000
BDM INTERNATIONAL, McLean, VA	703-484-7126
BOEING AIRCRAFT Manufacturer various platforms mounting IR systems	215-591-8399 817-280-6440
BRUNSWICK DEFENSE SYSTEMS, Deland, FLA AN/KAS-1 CWDD manufacturer	904-736-1700
CABOT ELECTRONIC MATERIALS DIV. Primary Ge producer	800-531-3677 215-367-1225
CHRYSLER CORP., Detroit, MI Buyer of catalysts	
CORNING GLASS Manufacturer of optical fiber	607-974-6623
EAGLE PICHER INDUSTRIES, Quapaw, OK Primary producer of Ge and Ge blanks	918-673-1650
EG&G JUDSON, INC. Various IR components	215-368-6900
ELECTRONIC SYSTEMS CO., CA	714-896-2176
ELECTRO-OPTICAL CORP, Dallas, TX IR modules for TOW, Dragon	214-349-0190
EMCORE, INC. Manufacturer of epitaxial growth machines	201-271-9090
ENGLEHARD METALS Non-ferrous metals trader	210-321-5999
ENSIGN-BICKFORD OPTICS Fiber Optics manufacturer	203-678-0371

EPITAXX, INC. IR element fabrication	609-452-1188
EXOTIC MATERIALS, INC. Manufacturer of windows and lenses	714-545-9425
FLIR SYSTEMS, INC., Portland, OR Manufacturer of FLIRS	503-684-3731
GALILEO ELECTRO-OPTICS CORP., Sturbridge, MA Night vision system	508-347-9191
GENERAL DYNAMICS VALLEY SYSTEMS DIVISION Passive IR homing Stinger missile	714-945-7000
GENERAL MOTORS CORP., Detroit, MI Buyer of catalysts	
HECLA MINING CORP. Primary Ge producer	208-769-4100
HUGHES AIRCRAFT CORP. (GM) Manufacturer of IR systems	818-702-2228
IBM, WATSON RESEARCH CENTER Electronic research	914-945-3884
INFRARED OPTICS, INC. Manufacturer of single crystal Ge	516-694-2977
JOHNSON MATTHEY ELECTRONIC MATERIALS DIV. Refiner of primary Ge and producer of CdHgTe	509-922-8724
KOLLMORGAN, INC., Northhampton, MA Optronic Mast producer	413-586-2330
LOCKHEED ELECTRONICS DIVISION Ga/Ge solar cells for Space Station	408-743-7157
MM/A-COM, INC., Cambridge, MA Manufacturer of wafers	617-272-3000
MAGNAVOX ELECTRO-OPTICAL SYSTEMS, Mahwah, NJ Manufacturer of various IR systems	201-529-1700
MARTIN MARIETTA, Orlando, FLA Manufacturers FLIRs for AH-64	
MCDONNELL DOUGLAS ELECTRONIC SYSTEMS DIV.	813-303-9161 714-896-4223

NORANDA MINERALS, INC. Primary Zinc producer	416-982-7324
PHOTONICS SPECTRA	413-499-0514
POLISHING CORP. OF AMERICA Manufacturer of wafers and lenses	408-988-6000
ROCKWELL INTERNATIONAL, Anaheim, CA Manufacturer various IR systems	714-762-4640
SCHOTT FIBER OPTICS, Southbridge, MA Optical fiber producer	508-765-9744
SOLAR ENERGY CORP., City of Industry, CA Manufacturer of GaAs/Ge solar cells for Space Station project	703-845-2588
SPAR AEROSPACE, Canada Manufacturer of AN/SAR-8 IRST	416-746-7252
SPECTRO LAB., INC., Sylmar, CA Manufacturer of large area solar cells for space power systems	
SPIRE CORP. ELECTRONIC MATERIALS DIV. Bedford, MA, Manufacturer of machinery for processing semiconductors	617-275-6000
TEXAS INSTRUMENTS, Dallas, TX Manufacturer of IR systems	214-480-1714
THE AEROSPACE CORP, El Segundo, CA	213-336-5000
UNITED TECHNOLOGIES, Jupiter, FL MANUFACTURER OF IR systems	407-775-4435
UNIVERSITY OF ARIZONA, OPTICAL SCIENCE CTR R&D on opto-electronics	602-621-4219
UNIVERSITY OF ROCHESTER, INSTITUTE OF OPTICS Opto-electreonics research	716-275-5248
U.S. AIR FORCE, Missile Guidance, Elgin, AFB	904-882-9091
U.S. AIR FORCE, ROME AIR DEVELOPMENT CENTER	617-377-3932
U.S. ARMY CONTRACTING OFFICE, N.J.	201-532-1015
U.S. ARMY NIGHT VISION CENTER, Ft. Belvoir, VA	703-664-6665

U.S. DEPARTMENT OF COMMERCE, Washington, D.C.	
U.S. NAVY, NAVAL SEA SYSTEMS COMMAND Buyer of IR systems for shipboard applications	202-602-6293
U.S. NAVY, NAVAL RESEARCH LABORATORY Washington, D.C.	202-767-3098
U.S. NAVY, NAVAL WEAPONS CENTER, Crane, IND	812-854-1241
U.S. NAVY, NAVAL WEAPONS CENTER, China Lake	619-939-2906
II-VI CORP., Saxonburg, PA Opto-electronic products producer	412-352-1504

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